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A review on the effects of frequency of oscillation on motion sickness

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Abstract

In support of the ADVANCE TDP (Advanced Vehicle Architecture for a Net-Enabled Combat Environment Technology Demonstration Project), and at the request of Director Armoured Vehicles Program Management (DAVPM), we undertook to provide a Phase 1 assessment on the effects of motion disturbance on the performance of operators based on a theoretical and comprehensive literature review. A comprehensive review on the effects of motion disturbance on human behaviour and well-being in all forms of transportation was completed. Based on information collected, a summary of the motion frequency and amplitude on human response was presented graphically. The main findings can be summarized as follows: The majority of information is obtained from ship-simulator or ship motion where vertical (heave) motion is the primary stimulus. Vertical motion does not correlate with the rate of carsickness. Fore-and-aft and lateral motion in the frequency range of 0.1-0.5 Hz is provocative in inducing carsickness. Postures and type of back/head rest could influence susceptibility to motion sickness. Laboratory studies indicated that the ability of the active suspension to protect against or contribute to motion sickness is influenced by whether or not the compensation is under the active control of the rider. Vertical motion frequencies below 0.5 Hz are generally more nauseogenic. Whole body vibration at 2 Hz and above can cause discomfort or injury but will not provoke motion sickness. Based on limited data, frequencies below 0.1 Hz lessen the possibility of motion sickness. The effect of vibration along the horizontal (x and y) axes on performance is unknown. Our recommendations include field studies on the incidence and severity of motion sickness in Canadian Forces enclosed armoured vehicles followed by simultaneous measurements of vehicle vibration, and physiological, psychophysical, and human performance in an enclosed vehicle during moving and stationary conditions in the second phase of the investigation.

Résumé

À l'appui du projet ADVANCE (Architecture de véhicule avancée pour un environnement de combat réseau-centrique) du Programme de démonstration de technologies, et à la demande du Directeur – Gestion de projet de véhicule blindé (D Gest PVB), nous avons entrepris une évaluation de phase 1 concernant les effets du mouvement sur la performance des opérateurs, d'après un examen documentaire théorique complet. Nous avons procédé à une étude complète des effets du mouvement sur le comportement et le bien-être humains dans tous les types de moyens de transport. En nous appuyant sur les renseignements recueillis, nous avons présenté un graphique résumant les effets de la fréquence et de l'amplitude du mouvement sur les réactions humaines. Les principales observations peuvent se résumer comme suit : la majorité de l'information est obtenue grâce à des simulateurs de navires ou porte sur des mouvements de navires dans lesquels le mouvement vertical (tangage) est le principal stimulus. Le mouvement vertical n'est pas corrélé au taux de mal de la route. Les mouvements longitudinaux et latéraux dans la plage de fréquence de 0,1 à 0,5 Hz peuvent induire le mal de la route. La posture et le type d'appui-dos ou d'appui-tête peuvent influer sur la susceptibilité au mal des transports. Des études en laboratoire ont révélé que la capacité de la suspension active de protéger contre le mal des transports ou d'y contribuer dépend du fait que le conducteur maîtrise activement ou non la compensation. Les mouvements verticaux à des fréquences inférieures à 0,5 Hz provoquent généralement plus de nausées. Une vibration du corps entier de 2 Hz ou plus peut entraîner un malaise ou des blessures, mais pas le mal des transports. D'après des données limitées, les fréquences inférieures à 0,1 Hz diminuent la possibilité de mal des transports. On ignore l'effet sur la performance de la vibration le long des axes horizontaux (x et y). Nous recommandons des études sur le terrain afin d'évaluer l'incidence et la gravité du mal des transports dans les véhicules blindés fermés des Forces canadiennes, suivies de mesures simultanées de la vibration des véhicules et de la performance physiologique et psychologique humaine dans un véhicule fermé en mouvement ou stationnaire dans la deuxième phase de l'enquête.

Executive summary

At the request of Director Armoured Vehicles Program Management (DAVPM) for the ADVANCE TDP (Advanced Vehicle Architecture for a Net-Enabled Combat Environment Technology Demonstration Project) a literature review on the effects of motion disturbance on human behaviour and well-being in all forms of transportation was performed. Our findings suggest that fore-and-aft and lateral motion in the frequency range of 0.1-0.5 Hz is provocative in inducing carsickness. Postures and type of back/head rest could influence susceptibility to motion sickness. Laboratory studies indicated that the ability of the active suspension to protect against or contribute to motion sickness is influenced by whether the compensation is under the active control of the rider. Vertical motion does not correlate with the rate of carsickness. Vertical motion below 0.5 Hz is generally more nauseogenic. Whole body vibration at 2 Hz and above can cause discomfort or injury but will not provoke motion sickness. Based on limited data, frequencies below 0.1 Hz lessen the possibility of motion sickness. The effect of vibration along the horizontal (x and y) axes on performance is unknown. We recommend that field studies on the incidence and severity of motion sickness in Canadian Forces enclosed armoured vehicles should be investigated in order to provide a comparison for future studies in vehicles with active suspensions.

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Sommaire

À la demande du Directeur – Gestion de projet de véhicule blindé (D Gest PVB), pour le projet ADVANCE (Architecture de véhicule avancée pour un environnement de combat réseau-centrique) du Programme de démonstration de technologies, nous avons procédé à un examen documentaire des effets du mouvement sur le comportement et le bien-être humains dans tous les modes de transport. Nos résultats laissent croire que les mouvements longitudinaux et latéraux dans la plage de fréquence de 0,1 à 0,5 Hz peuvent induire le mal de la route. La posture et le type d'appui-dos ou d'appui-tête peuvent influer sur la susceptibilité au mal des transports. Des études en laboratoire ont révélé que la capacité de la suspension active de protéger contre le mal des transports ou d'y contribuer dépend du fait que le conducteur maîtrise activement ou non la compensation. Les mouvements verticaux ne sont pas corrélés au taux de mal de la route. Les mouvements verticaux à des fréquences inférieures à 0,5 Hz provoquent généralement plus de nausées. Une vibration du corps entier de 2 Hz ou plus peut entraîner un malaise ou des blessures, mais pas le mal des transports. D'après des données limitées, les fréquences inférieures à 0,1 Hz diminuent la possibilité de mal des transports. On ignore l'effet sur la performance de la vibration le long des axes horizontaux (x et y). Nous recommandons des études sur le terrain afin d'évaluer l'incidence et la gravité du mal des transports dans les véhicules blindés fermés des Forces canadiennes de façon à effectuer des comparaisons en vue d'études futures dans les véhicules dotés d'une suspension active.

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Introduction

Many different forms of transport, from surface vehicles (land and sea) to air and space vehicles, cause motion discomfort with symptoms ranging from nausea to vomiting and/or retching in susceptible individuals. The most dreaded kind of motion sickness occurs on long duration voyages where the susceptible individuals often feel that they are effectively imprisoned in the nauseogenic environment. Seasickness is the most widely experienced form of this oppressive motion sickness; reports indicating such date back as far as the writers of the Greek epics. It seems likely that humans suffered from seasickness well before written records were made. With the exception of space sickness, also referred to as space adaptation syndrome, all true manifestations of mechanically induced motion sickness share an underlying physiological mechanism and a definable frequency range of oscillatory motion that is provocative. In addition to signs and symptoms of motion sickness, there are also documented changes in behaviour and performance such as: loss of well-being, decreased spontaneity, decreased readiness to perform and decreased muscular and eye-hand coordination. Enclosed cross-country vehicles, such as tanks, command and control vehicles (C2V), personnel carriers and future Multi-Mission Effects Vehicles (MMEV) can be highly nauseogenic although no figures on the incidence of motion disturbance in the Canadian Forces (CF) are available. A recent study on US Army personnel in C2Vs indicated that although only one out of eight subjects experienced vomiting, seven of the eight subjects reported other motion sickness symptoms (Cowings et al. 2001). The most frequently reported symptom was drowsiness, which occurred a total of 19 times. There was also an overall performance decrement during the C2V exercise. In another study moderate to severe motion sickness symptoms were reported by 74% of Marines tested after working at a computer workstation in a moving assault vehicle (Rickert 2000). Studies such as these, as well as anecdotal information reported from the line communities, suggest that soldier performance will be affected by motion; this issue should be examined and resolved to an acceptable level.

In the ADVANCE TDP (Advanced Vehicle Architecture for a Net-Enabled Combat Environment Technology Demonstration Project), there is a need to define the requirements of the active suspension in terms of vibration and absorbed power or impulse/acceleration, and how these may affect performance and susceptibility to motion sickness. Graphical representation of motion frequency, amplitude and corresponding human response related to field operations in an armoured vehicle would provide guidance to contractors in designing and evaluating of the active suspension system and in future modeling and prediction of human performance in such an environment. At the request of Director Armoured Vehicles Program Management (DAVPM), the objective of this review is to provide an assessment of the effects of various frequencies of motion disturbance on the well being of operators and passengers.

What is motion sickness?

Motion sickness is a maladaptive response to real and apparent motion (Cheung 2000). The cardinal signs of motion sickness are pallor and/or flushing in the facial area, cold sweating, vomiting or retching. The cardinal symptom of motion sickness is nausea; often, it is a precedent to vomiting. There are other signs and symptoms associated with motion sickness. They commonly occur in an orderly sequence as follows: stomach awareness, stomach discomfort, pallor, cold sweating, drowsiness/yawning, feeling of bodily warmth, increased salivation, nausea and vomiting/retching. The common after-effects are headache (especially frontal), apathy, anorexia, general malaise, dizziness, light-headedness or disorientation, flatulence, feeling miserable or depressed, especially with motion of long duration. The time scale for the development of symptoms is determined primarily by the intensity of the stimulus and the susceptibility of the individual. Therefore, individuals vary in their response: for instance, certain individuals may experience many of the above effects, feeling ill for a considerable amount of time, but they may not vomit; others may have a relatively short warning period (few signs and symptoms), vomit and feel better almost immediately. The rapid relief is partially attributable to the fact that salivation, stomach disturbance, respiratory and heart rate changes are also part of the organized chain of events that comprise the act of vomiting. If exposure to the motion continues, nausea increases in intensity and results in vomiting or retching. For the more susceptible individuals, the cyclical pattern may last for several hours or days. Dehydration and disturbance of electrolyte balances in the body brought about by the repeated vomiting compounds the disability.

The combination of sensorimotor systems involved in bringing about the onset of motion sickness and in the maintenance of spatial orientation awareness is identical. It involves the visual, vestibular (organs of balance) and the somatosensory receptors (tactile cues and proprioception). More than a century ago, Irwin (1881) suggested that sensory conflict (where sensory signals from the eyes and the organ of balance do not agree) was the principal cause of motion sickness. However, the prescribed conflict is not limited to signals from the sensory systems. These signals are also at variance with those that the central nervous system expects to receive. Therefore, the conflict theory of motion sickness holds that in a motion sickness environment, the pattern of sensory inputs concerning orientation and motion is in conflict with the pattern of inputs anticipated on the basis of past experience. This theory of a simple conflict causing sickness is insufficient, as it does not explain habituation to provocative stimuli or the after-effects of exposure to such stimuli. It does not explain why such a conflict should produce vomiting. Nevertheless the sensory conflict theory is satisfactory as all known causes of sickness can be accommodated by this theory and it suggests some useful preventive measures. Motion sickness is significant as it serves as a warning against inappropriate motor strategies that are causing undesired changes in vestibular function, and the subsequent disruption of normal sensorimotor integration. The ability of the human sensory system to resolve the motion experienced depends on the frequency of oscillation because the different senses do not all respond to the imposed acceleration. However, the severity of the signs and symptoms of motion sickness increases as a function of exposure time and acceleration intensity.

Early empirical and experimental observations suggested that vertical motion (heave) is the predominantly nauseogenic stimulus in the 1G (normal gravity, $1G = 9.8\ m/s^2$) environment. Data relating motion frequency to motion sickness are derived from early surveys conducted at sea. These surveys related passenger motion sickness questionnaire responses to their exposure to linear and angular motion. They concluded that vertical oscillation (heave motion) was the best predictor of motion sickness and that other linear (horizontal) or angular motions (roll, pitch and yaw) were less significant (Lawther and Griffin 1987). Because of the high inter-correlation between various types of ship motion, these surveys could not distinguish the separate contributions of each type of motion. As a result, early controlled laboratory studies employed largely vertical linear oscillation as the primary stimulus to provoke motion sickness and there were no controlled data relating frequency of motion to the nauseogenicity of horizontal motion until much later by Golding & Markey (1996). The sources of nauseogenic motion in different vehicular transports are examined below.

Land transport

Nausea and vomiting and other overt manifestations of motion sickness depend upon a certain periodicity rather than the magnitude (severity) of the motion. For example, early observations suggested that camel riders, whose mounts have a ponderously swaying (lateral acceleration) and lurching gait (fore-and-aft acceleration), tend to exhibit discomfort, instability and motion sickness. On the other hand, horse riding (high frequency trotting) is not conducive to motion sickness. It is known that a large number of people has been affected by motion sickness in road vehicles. An earlier survey of 300 undergraduates revealed that 58% had experienced some nausea from car travel and 33% recalled vomiting in cars before 12 years of age (Reason 1976). Surveys of the vibrations encountered in land transport vehicles indicate that the linear (horizontal) accelerations in the low frequency bands (< 0.5 Hz) are most relevant to motion sickness and their effects increase as a function of duration of exposure and the intensity of acceleration. A survey of 3256 long distance coach (Greyhound) passengers suggested that nausea occurrence was greater on routes classified as being predominantly cross-country where magnitudes of lateral vehicle motion were significantly higher. Their nausea and illness ratings increased with increased exposure to lateral coach motion at frequencies below 0.5 Hz (Turner 1992; Turner and Griffin 1999). Lateral motion and motion sickness incidence increased from the front to the rear of each vehicle. Sickness levels among passengers were greater with higher average magnitudes of fore-and-aft and lateral vehicle motion. However, motion in other axes correlated poorly with sickness. Similarly, a study on suburban car journeys reported that the fore-and-aft and lateral acceleration spectra were similar over the frequency range 0.1-0.5 Hz and were provocative in inducing motion sickness. These low frequency fore-and aft and lateral oscillations were more dependent on the driving behaviour of the driver than the characteristics of the vehicle. The motion sickness dose value (MSDV) in these axes was very similar (Griffin and Newman 2004). The British standard defines the MSDV (in $ms^{-1.5}$) as $(a^2t)^{1/2}$ where a is the root mean square value of the frequency weighted acceleration in (ms^{-2}) determined by linear integration over the period ‘t’ in seconds of the motion. It is suggested that the percentage of un-adapted adults who are likely to vomit may be estimated from 1/3 of MSDV.

Vertical accelerations in land transport tend to be in the higher frequency bands which are important for subjective “ride comfort” but are not provocative to motion sickness. Acceleration in the vertical direction is influenced by the vehicle suspension dynamics, with peaks between 1-2 Hz; however, the motion sickness dose value was appreciably lesser than fore-and-aft and lateral accelerations. It is generally accepted that vibrations of mainly mechanical origin above 1-2 Hz are not conducive to motion sickness, although they may cause impaired skilled performance, inefficiency, fatigue and nervous irritability. When the frequency is above this narrow range, the ride is judged to be too harsh because the high frequency vibrations are not attenuated in the human body tissues (frequencies between about

3 and 20 Hz are amplified by various resonances). When the suspension frequency is below 1 Hz, the ride is judged to be soft but susceptible passengers are prone to motion sickness. A resonance frequency of about 1 Hz with heavy damping for average passenger comfort was proposed as the compromise. Heavy working vehicles such as farm tractors and bulldozers driven over uneven ground typically generate severe, vertical (along the spinal axis) vibration spectra with measurable amounts of energy below 1 Hz (Guignard 1985). However, motion sickness is not a problem because the average accelerations at frequencies below 0.6 Hz are generally low and the duration of exposure is short with frequent stops and change in direction. Furthermore, the riders of such vehicle are generally the operators who are well adapted to such motions.

The field observation showing that low frequency fore-and-aft and lateral acceleration are effective stimuli in producing motion sickness was confirmed by laboratory studies (Golding and Markey 1996). It was demonstrated that at peak acceleration of 3.6 m/s^2 across the frequency range of 0.205 to 0.5 Hz, the nauseogenicity of motion increased significantly towards the lower frequencies. The duration of exposure required to elicit motion sickness was significantly shorter for 0.205 Hz than for 0.5 Hz at every level of sickness rating. Furthermore, with subjects sitting upright, horizontal motion at frequencies of 0.205, 0.35 and 0.5 Hz was found to be more nauseogenic than would be predicted by mathematical models that were developed using vertical oscillation as the stimulus. However, the relationship of frequency to nauseogenicity for horizontal motion was significantly less steep than what was reported for vertical motion. Controlled experiments suggested that there is a progressive increase in nauseogenicity as frequency decreases toward 0.2 Hz. A maximum nauseogenic potential occurring at 0.2 Hz was substantiated by Golding, et al. (2001).

Other environmental factors as well as the involvement of the subject in controlling the motion of the moving vehicle or other activities may also influence the immediacy and the inevitability of the motion sickness response. Guignard and McCauley (1982) suggest that carsickness is a common experience among passengers but not drivers of automobiles. As mentioned above, it is associated particularly with long unbroken rides on winding roads and with larger amplitudes of lateral (sway) motion normally encountered by the rear seat passengers in cars, and passengers sitting towards the back of buses where external visual reference is limited. Susceptibility to motion sickness increases especially for those who engage in visual tasks that requires internal reference that is continuously disrupted by motion and vibration; for example, reading in the car or working with a command and control or navigational visual display. The severity of motion sickness symptoms in land vehicles also depends upon the orientation of the passengers relative to the direction of linear acceleration. A recent study conducted in an armoured tracked C2V, which contained 4 work stations in an enclosed crew compartment with no outside view, suggested that all participants reported some degree of motion sickness, with 55% reporting moderate to severe malaise. There was a significant increase in motion sickness when conditions changed from park to move in all directions and from park to short halt (Cowings et al. 2001).

With no external view, horizontal fore-and-aft acceleration of 0.7 m/s^2 with less than 10% distortion (displacements up to 1 m and 0.25 Hz sinusoidal motion) was the most nauseogenic when subjects were sitting with a low backrest with eyes open. The least nauseogenic condition occurred with subjects sitting with a high backrest while exposed to fore-and aft oscillation. With the low backrest, the average illness rating was higher with motion in the fore-and-aft direction than with lateral direction, both with eyes open and with eyes closed. With a high backrest, the average illness rating tended to be less (although not statistically significant) with fore-and-aft motion than with lateral motion (Mills and Griffin 2000). Horizontal motion was found to be twice as nauseogenic as vertical motion when the subject was seated upright in both cases. This could be due to the increased requirement for postural control in the horizontal axis. Contrary to the general belief, the supine posture during vertical motion conferred no protection against motion sickness as compared with the upright posture. There was no difference in nauseogenicity between upright and supine postures in vertical motion. The non-significant trend was in the opposite direction (Golding et al. 2001) which confirmed early findings that there was no protective benefit against motion sickness for the supine posture (Johnson and Wendt, 1955).

The effects of active suspension

Accelerating, braking, and cornering in land vehicles produce horizontal forces at a frequency range of below 1 Hz, and a change in the gravitoinertial force and tilting of the inertial upright position that could provoke motion sickness. Compensatory alignment to the altered gravitoinertial force (GIF) as exhibited by most drivers who lean into the acceleration (align with the GIF) suggests reduced incidences of motion sickness. On the other hand, the passenger tends to be thrown outwards in the opposite direction and is generally more prone to motion sickness. However, a study by Golding et al. (2003) comparing conditions of active suspension under active and passive control with a condition with no active suspension indicated that other factors could be involved. A translational oscillatory motion with a sinusoidal 0.2 Hz, which produced a peak acceleration of 3.1 m/s^2 was used. The peak-to-peak displacement was 3.92 m, the peak translational velocity at the displacement centre of the track was 2.5 m/s, and the peak angular velocity of tilt of the head was 22 ^{o}/s. The results of this suggested that the ability of the active compensatory tilting (provided by active suspension) to protect against or contribute to motion sickness is influenced by whether or not the tilting is under the active control of the rider. If the active suspension that compensates for the misalignment during accelerating, braking and cornering is controlled by the subject (i.e., active control as experienced by the driver), the time to motion sickness end point is much longer than when there is no active suspension. However, if the occupants do not control the active suspension (i.e., external control as experienced by passengers), the time to motion sickness end-point was significantly shorter when there is an active suspension than where there is no active suspension. The findings cited above are consistent with earlier observations that having control over a moving vehicle greatly reduced the likelihood of motion sickness. In a controlled study of twenty-two pairs of yoked subjects, subjects who had control over their head movements and rotation reported significantly fewer motion sickness symptoms and less of a decrement in their well being as compared to the yoked subject without control (Rolnick & Lubow 1991). This suggested that voluntary production of sensory input initiates a different perceptual process from that caused by passive reception of similar input. Furthermore, it suggests also that when the subject generated the movement, there is a comparison of the original motor signal with the reafferent signal that takes place.

Land vehicles on tracks

In the late 19th century, train sickness was a common complaint due to poor suspension systems and riding stability of the vehicle. Current track-riding vehicles such as street cars, light rail transit and short trains that have brief journeys with frequent stops do not generate nauseogenic motion below 1 Hz. Therefore, passengers in these rail vehicles very rarely complain of motion sickness. Systematic studies by Vlaminck (1975) and Wichansky (1979) of passenger reactions to rail travel elicited a broad spectrum of complaints concerning train ride and interference with activities at high speed. There were also occasional complaints of motion sickness but they were relatively rare. However, trains with air suspension that utilize induction motors capable of attaining high speeds of 200 to 500 km/h may induce potentially nauseogenic motions. This type of high-speed train often involves terrain following with sufficient velocity that the natural undulations of the landscape pass beneath the vehicle. In Japan, high curve speed railway vehicles have peak vibration accelerations in the range of 0.5 to 1.0 Hz in the horizontal axis, and were responsible for the high rates of complaints of motion sickness among 119 passengers and 100 conductors (Ueno et al. 1986).

Seagoing vessels

Early studies in ships and hovercraft suggested that low frequency linear oscillation (heave) was identified as an important stimulus in causing seasickness (Lawther and Griffin 1987). Laboratory studies using vertical oscillation showed that sickness increases with decreasing frequency to at least about 0.2 Hz. For example, Alexander (1947) used a modified elevator to expose seated, blindfolded subjects to motion at frequencies of 0.22, 0.27, 0.37 and 0.53 Hz (magnitudes ranging from 1.96 to 5.47 m/s^2**)** for 20 minutes; there was a significant increase in nauseogenicity as frequency decreased. Their results also suggested that increases in motion magnitude did not necessarily increase the incidence of vomiting. McCauley et al. (1976) investigated the responses of over 500 subjects seated with their heads against a backrest with eyes opened in an enclosed cabin that oscillated vertically. Subjects were exposed to five frequencies 0.167, 0.25, 0.33, 0.5 and 0.6 Hz and various magnitudes from 0.278 to 5.5 m/s^2 root mean square (RMS) for a maximum of 2 hours. The highest percentage of vomiting was at 0.167 Hz, and the incidence of vomiting decreased gradually towards 0.3 Hz and then a more rapid decrease with higher frequencies. There was limited evidence suggesting that motion sickness incidence further decreased at frequencies below 0.167 Hz. Lawther and Griffin (1986) conducted a similar study, measuring the motions of a car ferry operating in the English Channel and the consequent sickness among passengers. Data were analyzed for 17 voyages of up to 6 hours in duration, involving over 4900 passengers. The results were similar to those of O'Hanlon and McCauley (1974) in that the strongest correlations between motion sickness incidence and motion were in the vertical (heave) direction, both in magnitude and duration of exposure. In addition, position aboard a vessel is a significant factor in how the subjects perceive a given motion.

In general, the frequency range of vertical motion that will induce motion sickness is from slightly below 0.1 Hz to slightly above 0.5 Hz. Lawther and Griffin (1986) and McCauley et al.(1976) reported that the highest incidence of vomiting during vertical oscillation occurs at 0.03 to 0.5 Hz. The same frequency range is used in the International Standards Organization

(ISO, 0.1 to 0.3 Hz) and British Standards Institution standards (BSI, 0.125 to 0.25 Hz). The force vector resulting from gravity and the imposed linear acceleration during heave motion is continually changing in magnitude and direction without the expected correlated signals from the semicircular canals. When the oscillation frequency is below 0.5 Hz, there is a phase error in the signaling of the linear motion by the otoliths that is in conflict with the transduction of the changing force by pressure receptors in the skin or with visual information. Therefore, there is a possibility of intermodality sensory conflict between the vestibular and visceral graviceptor signals (Gierke and Parker 1994). The frequency range of this potential conflict corresponds with the primary frequency range for motion sickness incidence in transportation. However, motion sickness does not occur as a result of exposure to vibration at frequencies above 2 Hz. Much higher frequencies such as 5 to 12 Hz or up to 20 Hz may cause severe discomfort or injury, but it does not provoke any signs and symptoms of motion sickness.

The effects of combined motion

The characteristic frequency of oscillation in a floating vessel is determined by the displacement of the vessel, i.e., its buoyancy. However, the dynamic characteristics of the vessel depend on the hull form and other factors in the design, operation and lading of the vessel. An incident wave tends to excite vertical oscillation (heave) of the vessel at its natural frequencies of buoyancy. It will excite the hull over a range of frequencies in heave, roll and pitch in which the vessel is compliant. In most vessels, this happens most often at vessel motion frequencies of 0.1 to 1 Hz, which is particularly nauseogenic to humans. Data collected by Lawther and Griffin (1986) were from very large passenger ships that typically have relatively small pitch and roll movements. It is not surprising that the traditional view that vertical motion is the principal stimulus for vibration induced motion sickness has been challenged, Wertheim et al. (1998) suggested that pitch and roll when combined with small heave motion, which in themselves are not sickness provoking, produce more motion sickness than claimed by the classic model. The motion parameters were: heave frequency at 0.1 Hz (with RMS between 25 and 32 cm; gravity (G) between 0.02 and 0.035), pitch frequency at 0.08Hz (with RMS between 4.9 to 9.9°; G between 0.01 and 0,022), roll frequency between 0.05 and 0.07 Hz (with RMS between 7.1 and 9.9°; G between 0.003 and 0.014). In addition, it is well known that smaller vessels such as Coast Guard patrol boats suffer to a greater extent from pitch and roll motions, and are more provocative in inducing seasickness.

Morton et al. (1947) exposed subjects to vertical, roll and pitch motions and found that at a frequency of 0.125 Hz, vertical motion combined with pitch oscillations resulted in 40% of subjects vomiting. When the vertical and pitch motions were combined with roll motion at 0.08 Hz, 33% of subjects vomited. As illness rates were similar both with and without roll motions it was concluded that roll motion did not contribute to sickness. Similar results were found when subjects were exposed to pitch and roll motion at frequencies of 0.115, 0.23 or 0.345 Hz with acceleration magnitudes in the range 5.5 to 33.3° m/s^2 RMS combined with 0.25 Hz vertical oscillation at a magnitude of 1.11 m/s^2 RMS. The incidence of sickness with roll and vertical motion combined was not significantly different from that with the vertical motion alone (McCauley et al. 1976). However, Frostberg (1999) investigated motion sickness occurrence in a group of 40 subjects exposed to 7 different combinations of lateral and roll oscillations and reported that combined roll and lateral oscillation caused greater sickness than did either roll oscillation or lateral oscillation alone. Wertheim et al. (1995)

indicated that combined pitch and roll motion at frequencies between 0.03 and 0.13 Hz and between ± 7 and ± 14° of rotation produced more sickness when combined with 0.1 Hz vertical oscillations of magnitudes in the range of 35-45 cm than when presented with no vertical motion. A more recent study suggests that sickness caused solely by roll oscillation through ± 8° over the frequencies of 0.025, 0.05, 0.1, 0.2 and 0.4 Hz produced low levels of motion sickness. The severity is less than the motion sickness caused by translational oscillation or with translational oscillation combined with roll oscillation (Howarth and Griffin 2003).

In general, the larger the vessels, the less likely seasickness will afflict the ship's complement at a given sea state and condition (Wiker et al. 1979). However, large mobile drilling platforms and supertankers of immense displacement and dimensions with high structural flexibility and low inherent structural damping can exhibit vibrations frequencies below 2 Hz. Naval vessels such as light cruisers and destroyers tend to heave, pitch and roll at frequencies of 0.13 to 0.33 Hz that are particularly nauseogenic. Because of the heave component of the composite motion of the vessel, susceptibility to seasickness can be shown to increase monotonically as a simple geometric function of the lateral distance of the subject from the effective centres of rotation of the vessel (Bittner and Guignard, 1985). Smaller vessels such as passenger and pleasure craft can experience violent motions that include abrupt yawing and large amplitude roll and pitch and heave in severe weather that will provoke motion sickness as well as shipboard injury.

Aircraft

The major motion disturbance to aircrew and passengers in most flight conditions comes from vertical (along the spinal axis) motion and the rotational oscillation in roll, pitch and yaw. At both low and high altitude, the rigid body displacements caused by rough air typically occur at frequencies below 1 Hz, and most of the energy of motion-inducing, aircraft gust responses, is in the frequency spectrum below 0.5 Hz (Benson 1978). Low altitude thermal turbulence is the major and common source of nauseogenic motion in helicopters, military aircraft for reconnaissance, search and rescue (typically flight operations below 1000 m relative altitude) and bombers. For example, airsickness was found to be a frequent occurrence in all crewmembers in all crew positions except the pilot and co-pilot positions in the B-52, primarily during low-level flights. The impact of gust upon the airframe can cause a structural vibration at frequencies of 1 to 5 Hz. The incidence of airsickness appears to be higher among aft-facing passengers (Geeze & Pierson 1986; Strongin and Charlton 1991). A survey of 923 passengers during short-haul commercial flights indicated that the incidence of illness and nausea were positively correlated with motion sickness dose values in both the lateral and the vertical directions (below 0.5 Hz), but not in the fore-and-aft direction; sickness generally increased with increasing magnitudes in both the lateral and vertical direction (Turner et al. 2000).

The effects of magnitude and duration of motion

For vertical sinusoidal oscillation between 0.167 – 0.5 Hz, there is a clear increase in sickness with increasing oscillation magnitude (McCauley et al. 1976). In laboratory studies, higher magnitude of motions provokes vomiting earlier than low magnitude motions. Severe motion sickness symptoms and signs can be provoked in the laboratory using vestibular Coriolis cross coupling, which is a vestibular organ effect of tilting the head during whole-body rotation. Little is known regarding translational motion-induced, motion sickness except that it takes considerably longer exposure before translational oscillation causes nausea and vomiting. If a subject has already succumbed to motion sickness, a sudden short duration of severe translational oscillation could provoke vomiting.

The effects of motion sickness on performance

Motion sickness has a direct and instantaneous mechanical disruption on human visual motor activity, task performance and human locomotion. Continuous oscillatory motions (acting through sensory and neurophysiological mechanisms), also impair cognitive performance in a time-dependent manner; induces cumulative stress; and adversely affects the pattern and quality of sleep, rest and wakefulness. For example, loss of well-being can distract the operator from assigned duties and cause a decrease in spontaneity and activity. There is a decrease in muscular co-ordination and eye-hand coordination, ability to estimate time and decrease in the performance of arithmetic computation (Money 1970). The person is usually subdued and quiet. The sickness, nausea, drowsiness and apathy associated with motion sickness can significantly reduce one's motivation to conduct their required tasks and duties. It was suggested by Birren (1949) that tasks associated with personal hygiene and health are likely to be unaffected except in the most severe forms of sickness. However, the person's ability to conduct daily work may be affected as a result of motion sickness. It should be emphasized that the impact of motion sickness on performance varies independently from reported symptoms. There are many individuals who vomit that are apparently able to carry out their duties efficiently both immediately before and after the vomiting episode. Others who report nothing more than general malaise or slight nausea are apparently reduced to such a state of inefficiency over a relatively long period that the value of their trip is largely negated.

Conclusion

Studies in aircraft and ships are consistent with the suggestion that frequencies below 0.5 Hz are more nauseogenic than higher frequencies. Whole-body vibration at 2 Hz and above can cause severe discomfort or injury but will not produce signs and symptoms of motion sickness. There have been very few studies using frequencies below 0.1 Hz, but it is often assumed that the sensitivity to motion sickness decreases. A widespread assumption that low frequency oscillation of cars causes sickness is based on the observation that this motion causes sickness at sea. Laboratory experimental evidence suggests that vertical motions recorded in cars do not correlate with sickness rates. More relevant is the amount of low-frequency horizontal motion in cars that are dependent on the car itself, the bends of the road, and the driver’s activities (speed, acceleration and deceleration). The ability of active suspension (compensatory tilting) to protect against or contribute to motion sickness can be influenced by whether the tilting is under the active control of the person as experienced by the driver, or under external control as experienced by the passenger. The effects of frequency on motion sickness are summarized in Figure 1 under Annex

In summary:

- The majority of information on motion sickness is obtained from ship-simulator or ship-motion studies where vertical (heave) motion is the primary stimulus.

- Vertical motion does not correlate with the rate of carsickness.

- Fore-and-aft and lateral motion in the frequency range of 0.1-0.5 Hz is provocative in inducing carsickness.

- Posture and type of back/head rest could influence susceptibility to motion sickness.

- Laboratory studies indicate that the ability of the active suspension to protect against or contribute to motion sickness is influenced by whether or not the compensation is under the active control of the rider.

- Vertical motion frequencies below 0.5 Hz are generally more nauseogenic.

- Whole-body vibration at 2 Hz and above can cause discomfort or injury but will not provoke motion sickness.

Annex A

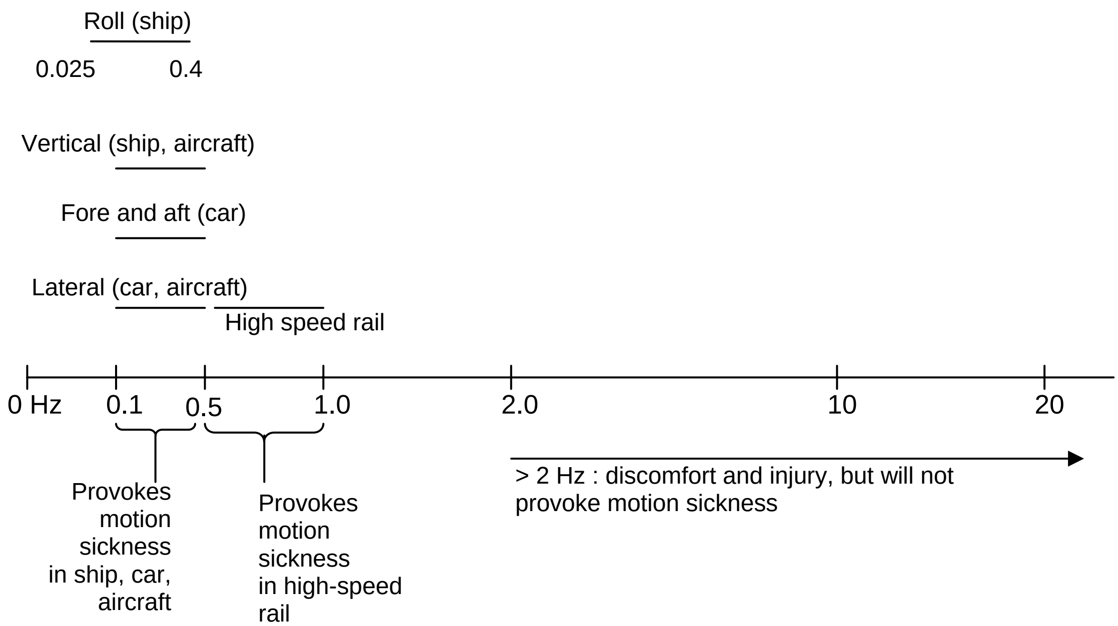

Figure 1. *Effects of frequency on motion sickness*

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List of symbols/abbreviations/acronyms/initialisms

ADVANCE	Advanced Vehicle Architecture for a Net-Enabled Combat Environment
C2V	Command and Control Vehicles
CF	Canadian Forces
DAVPM	Director Armoured Vehicles Program Management
DND	Department of National Defence
G	Gravity
GIF	Gravitoinertial Force
MMEV	Multi-Mission Effects Vehicles
MSDV	Motion Sickness Dose Value
RMS	Root Mean Square
TDP	Technology Demonstration Project
US	United States

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(U) In support of the ADVANCE TDP (Advanced Vehicle Architecture for a Net−Enabled Combat Environment, Technology Demonstration Project), and at the request of Director Armoured Vehicles Program Management (DAVPM), we undertook to provide a Phase 1 assessment on the effects of motion disturbance on the performance of operators based on a theoretical and comprehensive literature review. A comprehensive review on the effects of motion disturbance on human behaviour and well−being in all forms of transportation was completed. Based on information collected, a summary of the motion frequency and amplitude on human response was presented graphically. The main findings can be summarized as follows: The majority of information is obtained from ship−simulator or ship motion where vertical (heave) motion is the primary stimulus. Vertical motion does not correlate with the rate of carsickness. Fore−and−aft and lateral motion in the frequency range of 0.1−0.5 Hz is provocative in inducing carsickness. Postures and type of back/head rest could influence susceptibility to motion sickness. Laboratory study indicated that the ability of the active suspension to protect against or contribute to motion sickness is influenced by whether the compensation is under the active control of the rider. Vertical motion frequencies below 0.5Hz are generally more nauseogenic. Whole body vibration at 2 Hz and above can cause discomfort or injury but will not provoke motion sickness. Based on limited data, frequencies below 0.1 Hz lessen the possibility of motion sickness. The effect of vibration along the horizontal (x and y) axis on performance is unknown. Our recommendations include field studies on the incidence and severity of motion sickness in CF enclosed armoured vehicles followed by simultaneous measurements of vehicle vibration, physiological, psychophysical, and human performance in an enclosed vehicle during moving and stationary conditions in the second phase of the investigation.

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(U) motion sickness; frequency of oscillation

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